Quintessence – the Dark Energy in the Universe?

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Abstract

Quintessence – the energy density of a slowly evolving scalar field – may constitute a dynamical form of the homogeneous dark energy in the universe. We review the basic idea and indicate observational tests which may distinguish quintessence from a cosmological constant.

The idea of quintessence originates from an attempt to understand the smallness of the "cosmological constant" or dark energy in terms of the large age of the universe [1]. As a characteristic consequence, the amount of dark energy may be of the same order of magnitude as radiation or dark matter during a long period of the cosmological history, including the present epoch. Today, the inhomogeneous energy density in the universe – dark and baryonic matter – is about $\rho_{inhom} \approx (10^{-3}\text{eV})^4$. This number is tiny in units of the natural scale given by the Planck mass $M_p = 1.22 \cdot 10^{19}$ GeV. Nevertheless, it can be understood easily as a direct consequence of the long duration of the cosmological expansion: a dominant radiation or matter energy density decreases $\rho \sim M_p^2 t^{-2}$ and the present age of the universe is huge, $t_0 \approx 1.5 \cdot 10^{10}$ yr. It is a natural idea that the homogeneous part of the energy density in the universe – the dark energy – also decays with time and therefore turns out to be small today[1].

A simple realization of this idea, motivated by the anomaly of the dilatation symmetry, considers a scalar field ϕ with an exponential potential [1]

$$\mathcal{L} = \sqrt{g}\left\{\frac{1}{2}\partial^\mu\phi\partial_\mu\phi + V(\phi)\right\} \quad , \quad V(\phi) = M^4\exp(-\alpha\phi/M) \tag{1}$$

with $M^2 = M_p^2/16\pi$. In the simplest version ϕ couples only to gravity, not to baryons or leptons. Cosmology is then determined by the coupled field equations for gravity and the scalar "cosmon" field in presence of the energy density ρ of radiation or matter. For a homogeneous and flat universe they read ($n = 4$ for radiation and $n = 3$ for nonrelativistic matter)

$$\begin{aligned} &H^2 = \frac{1}{6M^2}(\rho + \frac{1}{2}\dot{\phi}^2 + V), \\ &\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0, \\ &\dot{\rho} + nH\rho = 0. \end{aligned} \tag{2}$$

One finds that independently of the precise initial conditions the behavior for large t approaches an exact "cosmological attractor solution" (or "tracker solution") where the scalar kinetic and potential energy density scale proportional to matter or radiation [1]

$$\phi = \frac{2M}{\alpha}\ln(t/\bar{t}) \ , \quad \frac{1}{2}\dot{\phi}^2 = \frac{2M^2}{\alpha^2}t^{-2} \ , \quad V = \frac{2M^2}{\alpha^2}\frac{(6-n)}{n}t^{-2}, \tag{3}$$

with the usual decrease of the Hubble parameter H

$$H = \frac{2}{n}t^{-1} \quad , \quad \rho \sim t^{-2}. \tag{4}$$

This simple model predicts a fraction of dark energy (as compared to the critical energy density $\rho_c = 6M^2H^2$) which is constant in time

$$\Omega_d = (V + \frac{1}{2}\dot{\phi}^2)/\rho_c = \rho_\phi/\rho_c = \frac{n}{2\alpha^2} \tag{5}$$

[1] For some related ideas see ref. [2], [3].

both for the radiation-dominated ($n = 4$) and matter-dominated ($n = 3$) universe $((\Omega_d + \rho/\rho_c) = 1)$. This would lead to a natural explanation why today's dark energy is of the same order of magnitude as dark matter.

The qualitative ingredients for the existence of the stable attractor solution[2] (3), (4) are easily understood: for a large value of $V(\phi)$ the force term in eq. (2), $\partial V/\partial\phi = -(\alpha/M)V$, is large, and the dark energy decreases faster than matter or radiation. In the opposite, when the matter or radiation energy density is much larger than V, the force is small as compared to the damping term $3H\dot{\phi}$ and the scalar "sits and waits" until the radiation or matter density is small enough such that the overdamped regime ends. Stability between the two extreme situations is reached for $V \sim \rho$.

From present observations one concludes that today's fraction of dark energy is rather large

$$\Omega_d^0 = 0.6 - 0.7. \tag{6}$$

On the other hand, structure formation would be hindered by a too large amount of dark energy [7], and one infers an approximate upper bound for the amount of dark energy during structure formation (for details see below)

$$\Omega_d^{sf} \lesssim 0.2. \tag{7}$$

As a consequence, the fraction of dark energy must have increased in the recent epoch since the formation of structure. This implies a negative equation of state for quintessence [8], [9] $w_d = p_\varphi/\rho_\varphi < 0$ and can lead to a universe whose expansion is presently accelerating, as suggested by the redshifts of distant supernovae [10].

The pure exponential potential in eq. (1) is too simple to account for the recent increase in Ω_d. Possible modifications of the basic idea of quintessence include the use of other potentials [1], [4], [11]-[15], the coupling of quintessence to dark matter [6], [16], nonstandard scalar kinetic terms [17] or the role of nonlinear fluctuations [18]. We note that these ideas may not be unrelated, since the presence of large fluctuations can modify the effective field equations (e.g. change the effective cosmon potential and kinetic term) and lead to a coupling between quintessence and dark matter [18].

In view of the still very incomplete theoretical understanding of the origin of quintessence the choice of an appropriate effective action for the cosmon is mainly restricted by observation. For comparison with observation and a discussion of naturalness of various approaches [19] we find it convenient to work with a rescaled cosmon field such that the scalar field lagrangian reads

$$\mathcal{L}(\varphi) = \frac{1}{2}\,(\partial\varphi)^2\,k^2(\varphi) + \exp[-\varphi]\,. \tag{8}$$

Here and in what follows all quantities are measured in units of the reduced Planck mass $\overline{M}_P$, i.e., we set $\overline{M}_P^2 \equiv M_P^2/(8\pi) \equiv (8\pi G_N)^{-1} = 2M^2 = 1$. The lagrangian of Eq. (8) contains a simple exponential potential $V = \exp[-\varphi]$ and a non-standard kinetic term

[2]For more details see refs. [4], [5], [6].

with $k(\varphi) > 0$. If one wishes, the kinetic term can be brought to the canonical form by a change of variables. Introducing the field redefinition

$$\phi = K(\varphi) \qquad , \qquad k(\varphi) = \frac{\partial K(\varphi)}{\partial \varphi} \tag{9}$$

one obtains

$$\mathcal{L}(\phi) = \frac{1}{2}(\partial\phi)^2 + \exp[-K^{-1}(\phi)] \,. \tag{10}$$

The exponential potential in eq. (1) corresponds to a constant

$$k = \frac{1}{\sqrt{2}\alpha} \tag{11}$$

We restrict our discussions to potentials that are monotonic in ϕ. (Otherwise, the value of the potential at the minimum must be of the order of today's cosmological constant, with $V_{min} \approx 10^{-120}$. Cosmologies of this type are discussed in [11], [14].) All monotonic potentials can be rescaled to the ansatz Eq. (8). An initial value of φ in the vicinity of zero corresponds then to an initial scalar potential energy density of order one. We consider this as a natural starting point for cosmology in the Planck era. As a condition for naturalness we postulate that no extremely small parameter should be present in the Planck era. This means, in particular, that $k(0)$ should be of order one. Furthermore, this forbids a tuning to many decimal places of parameters appearing in $k(\varphi)$ or the initial conditions. For natural quintessence all characteristic mass scales are given by $\overline{M}_P$ in the Planck era. The appearance of small mass scales during later stages of the cosmological evolution is then a pure consequence of the age of the universe (and the fact that $V(\varphi)$ can be arbitrarily close to zero). In addition, we find cosmologies where the late time behaviour is independent of the detailed initial conditions particularly attractive. For such tracker solutions [1, 6, 4, 5, 8] no detailed understanding of the dynamics in the Planck era is needed. It is indeed possible to find [19] viable cosmological solutions with high present-day acceleration which are based on functions $k(\varphi)$ that always remain $\mathcal{O}(1)$.

It is convenient to analyse the cosmological evolution using the scale factor a instead of time as the independent variable. In this case, the evolution of matter and radiation energy density is known explicitly and one only has to solve the set of the two differential equations for the homogeneous dark energy density ρ_φ and the cosmon field φ

$$\frac{d\ln\rho_\varphi}{d\ln a} = -3(1+w_\varphi) \ , \qquad \frac{d\varphi}{d\ln a} = \sqrt{6\Omega_T/k^2(\varphi)} \ , \tag{12}$$

with $\Omega_T = T/(3H^2)$ the fraction of kinetic field energy and $w_d = p_\varphi/\rho_\varphi$. Here the cosmon kinetic energy is denoted by $T = \dot{\varphi}^2 k^2(\varphi)/2$ whereas $p_\varphi = T - V$ and $\rho_\varphi = T + V$ specify the equation-of-state of quintessence. Thus, more explicitly, the cosmology is governed by four equations for the different components of the energy density $\rho_m, \rho_r, \rho_\varphi$ and φ

$$\begin{aligned} &\frac{d\ln\rho_m}{d\ln a} = -3\,(1+w_m) \ , \qquad &&\frac{d\ln\rho_r}{d\ln a} = -3\,(1+w_r) \ , \\ &\frac{d\ln\rho_\varphi}{d\ln a} = -6\left(1 - \frac{V(\varphi)}{\rho_\varphi}\right) \ , \qquad &&\frac{d\varphi}{d\ln a} = \sqrt{\frac{6\,(\rho_\varphi - V(\varphi))}{k^2\,(\varphi)(\rho_m + \rho_r + \rho_\varphi)}} \ , \end{aligned} \tag{13}$$

where $w_m = 0$ and $w_r = 1/3$ for matter and radiation respectively. For our exponential potential $V = \exp[-\varphi]$, the last equation can be rewritten as

$$\frac{d\ln V}{d\ln a} = -\sqrt{\frac{6\,(\rho_\varphi - V)}{k^2\,(-\ln V)(\rho_m + \rho_r + \rho_\varphi)}}\,. \tag{14}$$

We note that today's value of ρ_φ plays the role of ϵ_{vac} and the fraction of dark energy is therefore $\Omega_d = \rho_\varphi/(3H^2)$. For a rough orientation, today's value of φ must be $\varphi_0 \simeq 276$ for all solutions where the present potential energy is of the order of ϵ_{vac}.

The simplest case, $k(\varphi) = k = \text{const.}$, (cf. eq. (11)) corresponds to the original quintessence model [1]. If $k^2 < 1/n$ (with $n = 3(1 + w_{r,m})$ for radiation and matter domination, respectively), then the scalar field energy ρ_φ follows the evolution of the background component ρ in the way described above, with $\Omega_d = nk^2$. This attractor solution can be easily retrieved from Eqs. (13) and (14) by noting the constancy of ρ_φ/ρ and V/ρ. For $k^2 > 1/n$ the cosmological attractor is a scalar dominated universe [1, 6, 5, 20] with $H = 2k^2 t^{-1}$, $w_d = 1/(3k^2) - 1$. However, it has been emphasized early [1] that there is actually no reason why $k(\varphi)$ should be exactly constant and that interesting cosmologies may arise from variable $k(\varphi)$. In particular, one may imagine an effective transition from small k (small Ω_d) in the early universe (nucleosynthesis etc.) to large k ($\Omega_d \simeq 1$) today [6, 9, 15, 21].

A particularly simple case of a φ dependent kinetic coefficient $k(\varphi)$ is obtained if k suddenly changes from a small number $k < 0.22$ (consistent with nucleosynthesis and structure formation bounds) to a number above the critical value $1/\sqrt{n}$. Consider, for example, the function

$$k(\varphi) = k_{min} + \tanh(\varphi - \varphi_1) + 1 \qquad \text{(with} \quad k_{min} = 0.1\,,\ \ \varphi_1 = 276.6\,)\,, \tag{15}$$

that gives rise to the cosmological evolution of Fig. 1. This "leaping kinetic term quintessence" model, which completely avoids the explicit use of very large or very small parameters, realizes all the desired features of quintessence [19]. The homogeneous dark energy density tracks below the background component in the early universe ($k = 0.1$) and then suddenly comes to dominate the evolution when k rises to a value $k = 2.1$ approximately today. With a tuning on the percent level (the value of φ_1 has to be appropriately adjusted) realistic present-day values of Ω_d and w_d^0 can be realized. In the above example, one finds $\Omega_d^0 = 0.70$ and $w_d^0 = -0.80$. Note that, due to the extended tracking period, the late cosmology is completely insensitive to the initial conditions. In the example of Fig. 1, the evolution starts at the Planck epoch with a total energy density $\rho_{tot} = 1.0$, $\varphi = 2.0$ and $\dot\varphi = 0$ (corresponding to $\Omega_d = 0.14$). We have checked explicitly other initial conditions, e.g., with Ω_d near one. The present day value w_d^0 can be forced to be even closer to -1 if the leap of $k(\varphi)$ is made sharper or the final value of k is made higher by a simple generalization of Eq. (15). Thus, all scenarios between a smoothly rising quintessence contribution and a suddenly emerging "cosmological constant" can be realized.

As the theoretical understanding of the origin of quintessence from fundamental physics remains very incomplete, a large variety of effective potentials and kinetic terms

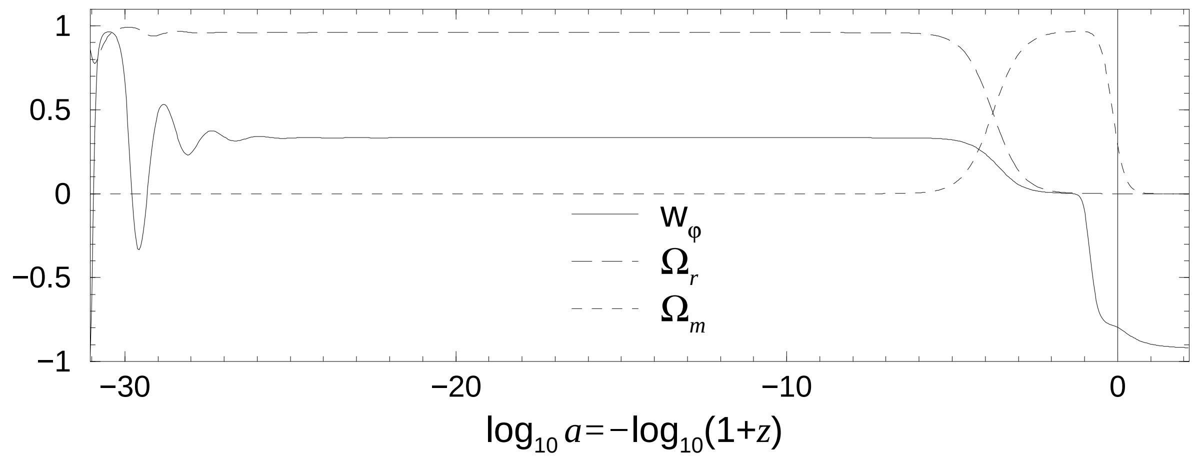

Figure 1: Cosmological evolution with a leaping kinetic term. We show the fraction of energy in radiation (Ω_r) and matter (Ω_m) with $\Omega_d = 1 - \Omega_r - \Omega_m$. The equation of state of quintessence is specified by w_φ.

for the cosmon can be conceived. One would therefore like to use the available information from observation to determine the characteristic features of quintessence in a way that is as model-independent as possible. The basic feature which distinguishes quintessence from a cosmological constant is the time evolution of the dark energy. For a cosmological constant the energy density is constant, and therefore $\Omega_d \sim t^2$ becomes irrelevant in the early universe. In contrast, the time evolution of $\Omega_d(t)$ is more complex for quintessence. In particular, a relevant fraction of the energy density may have been dark energy also in earlier epochs of the universe. The effects of this "early dark energy" may lead to observable consequences. We therefore aim to gather information about the value of $\Omega_d(t)$ at various characteristic moments of the cosmological evolution. As an alternative to an overall fit of the data, which typically involves many cosmological parameters and has to be done, in principle, for a large variety of different quintessence models, we pursue here a search for "robust quantities" that can "measure" $\Omega_d(t)$ for different t. Typical examples are the determination of the present fraction in dark energy $\Omega_d^0 \approx 0.6 - 0.7$ or the bound from nucleosynthesis [1], [22] $\Omega_d^{ns} \lesssim 0.2$.

As an example we discuss here how the amount of dark energy at the time of last scattering, Ω_d^{ls}, may be extracted from cosmic microwave background (CMB) anisotropies. Recent measurements of the CMB [23, 24] show three peaks as distinct features, seeming to confirm beyond any reasonable doubt the inflationary picture of structure formation from predominantly adiabatic initial conditions. It was demonstrated [25, 26, 27] that the location of the CMB peaks depends on three dark-energy related quantities: the amounts of dark energy today Ω_d^0 and at last scattering $\overline{\Omega}_d^{\rm ls}$ as well as its time-averaged equation of state $\overline{w}_0$.

The CMB peaks arise from acoustic oscillations of the primeval plasma just before the universe becomes translucent. The angular momentum scale of the oscillations is set

by the *acoustic scale* l_A which for a flat universe is given by

$$l_A = \pi \frac{\tau_0 - \tau_{\rm ls}}{\bar{c}_s \tau_{\rm ls}}, \tag{16}$$

where τ_0 and $\tau_{\rm ls}$ are the conformal time today and at last scattering and $\bar{c}_s$ is the average sound speed before decoupling. The value of l_A can be calculated simply, and for flat universes is given by [25]

$$l_A = \pi \bar{c}_s^{-1} \left[\frac{F(\Omega_d^0, \overline{w}_0)}{(1-\overline{\Omega}_d^{\rm ls})^{1/2}} \left\{ \left(a_{\rm ls} + \frac{\Omega_{\rm r}^0}{1-\Omega_d^0} \right)^{1/2} - \left(\frac{\Omega_{\rm r}^0}{1-\Omega_d^0} \right)^{1/2} \right\}^{-1} - 1 \right], \tag{17}$$

The conformal time

$$\tau_0 = 2 H_0^{-1} (1-\Omega_d^0)^{-1/2} F(\Omega_d^0, \bar{w}_0) \tag{18}$$

involves the integral

$$F(\Omega_d^0, \overline{w}_0) = \frac{1}{2} \int_0^1 \mathrm{d}a \left(a + \frac{\Omega_d^0}{1-\Omega_d^0} a^{(1-3\overline{w}_0)} + \frac{\Omega_{\rm r}^0 (1-a)}{1-\Omega_d^0} \right)^{-1/2}. \tag{19}$$

Here $\Omega_{\rm r}^0, \Omega_d^0$ are today's radiation and quintessence components, $a_{\rm ls}$ is the scale factor at last scattering (if $a_0 = 1$), $\bar{c}_s, \overline{\Omega}_d^{\rm ls}$ are the average sound speed and quintessence components before last scattering [25] and $\overline{w}_0$ is the Ω_d-weighted equation of state of the Universe

$$\overline{w}_0 = \int_0^{\tau_0} \Omega_d(\tau) w_d(\tau) \mathrm{d}\tau \times \left(\int_0^{\tau_0} \Omega_d(\tau) \mathrm{d}\tau \right)^{-1}. \tag{20}$$

The location of the peaks is influenced by driving effects and we compensate for this by parameterising the location of the m-th peak l_m as in [28]

$$l_m \equiv l_A \left(m - \varphi_m \right). \tag{21}$$

The reason for this parameterization is that the phase shifts φ_m of the peaks are determined predominantly by pre-recombination physics, and are independent of the geometry of the Universe. The values of the phase shifts are typically in the range $0.1 \ldots 0.5$ and depend on the cosmological parameters $\Omega_b h^2, n, \overline{\Omega}_\varphi^{\rm ls}$ and the ratio of radiation to matter at last scattering $r_\star = \rho_r(z_\star)/\rho_m(z_\star)$.

It was shown [26] that φ_3 is relatively insensitive to cosmological parameters, and that by assuming the constant value $\varphi_3 = 0.341$ we can estimate l_A to within one percent if the location of the third peak l_3 is measured, via the relation $l_A = l_3/(3-\varphi_3)$. The measurement of a third peak in the CMB spectrum by BOOMERANG [23] now allows us to extract the acoustic scale l_A and use this as a constraint on cosmological models. (See Fig. 2). From the conservative assumption that $800 < l_3 < 900$,one gets the bound

$$296 \leq l_A \leq 342 \tag{22}$$

(The BOOMERANG analysis [29] indicates $l_A = 316 \pm 8$.) For a given value of the Hubble parameter $h = 0.65$ and present dark energy $\Omega_d^0 = 0.6$ one finds [25] for the "leaping kinetic term quintessence" discussed above with $\Omega_d^{ls} = 0.15$ a value $l_A = 300$ whereas a

cosmological constant yields $l_A = 296$. On the other hand, power law quintessence [4] leads to $l_A = 270$. Larger values of Ω_d^0 increase l_A (cf. eq. (17)) and similar for larger values of h. Using constraints on Ω_d^0 and h from other observations a distinction between different quintessence models becomes possible already with the present data [27]. For example, power law potentials seem to be disfavored.

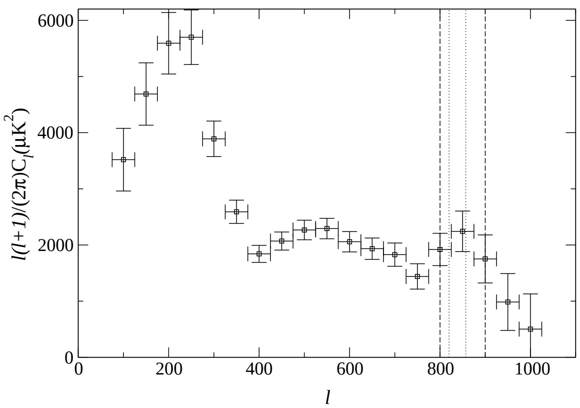

Figure 2: The CMB anisotropy power spectrum as measured by BOOMERANG [23]. The inner vertical lines show the region $820 < l_3 < 857$ as calculated by the BOOMERANG team [29], and the outer lines our more conservative region $800 < l_3 < 900$.

Another possible benchmark for determining the amount of dark energy in early cosmology is the formation of structure [30]. In particular, σ_8, the rms density fluctuation averaged over $8h^{-1}$Mpc spheres, is a sensitive parameter. The COBE [31] normalization [32] of the CMB power spectrum determines σ_8 for any given model by essentially fixing the fluctuations at decoupling. This prediction is to be compared to values of σ_8 infered from other observations, such as cluster abundance constraints which yield [33]

$$\sigma_8 = (0.5 \pm 0.1)\Omega_m^{-\gamma}, \tag{23}$$

where γ is slightly model dependent and usually $\gamma \approx 0.5$. A model where these two σ_8 values do not agree can be ruled out. Standard Cold Dark Matter (SCDM) without dark energy [3] for instance gives $\sigma_8^{\rm cmb} \approx 1.5,\ \sigma_8^{\rm clus.} \approx 0.5 \pm 0.1$ and is hence incapable of meeting both constraints.

Within the standard scenario[4] where structure formation proceeds by the gravitational clumping of cold dark matter one can estimate [30] the CMB-normalized σ_8-value for a very general class of quintessence models Q just from the knowledge of the "background solution" $[\Omega_{\rm d}(a),\ w_{\rm d}(a)]$ and the σ_8-value of the ΛCDM model Λ with the same amount of dark energy today given by a cosmological constant, i.e. with $\Omega_\Lambda^0 = \Omega_{\rm d}^0$:

$$\frac{\sigma_8(Q)}{\sigma_8(\Lambda)} \approx \left(a_{\rm eq}\right)^{3\,\bar{\Omega}_{\rm d}^{\rm sf}/5}\left(1-\Omega_\Lambda^0\right)^{-\left(1+\bar{w}^{-1}\right)/5}\sqrt{\frac{\tau_0(Q)}{\tau_0(\Lambda)}}. \tag{24}$$

[3] and $h = 0.65,\ \hat{n} = 1, \Omega_{\rm b}h^2 = 0.021,\ \Omega_{\rm m}^0 = 1$

[4] See [18] for an alternative with cosmon dark matter.

If Q is a model with 'early quintessence', $\bar{\Omega}_{\rm d}^{\rm sf}$ is an average value for the fraction of dark energy during the matter dominated era, before $\Omega_{\rm d}$ starts growing rapidly at scale factor $a_{\rm tr}$:

$$\bar{\Omega}_{\rm d}^{\rm sf} \equiv [\ln a_{\rm tr} - \ln a_{\rm eq}]^{-1} \int_{\ln a_{\rm eq}}^{\ln a_{\rm tr}} \Omega_{\rm d}(a) \, {\rm d} \ln a. \tag{25}$$

(For a model without early quintessence, $\bar{\Omega}_{\rm d}^{\rm sf}$ is zero.) The effective equation of state of quintessence $\bar{w}$, is an average value for $w_{\rm d}$ during the time in which $\Omega_{\rm d}$ is growing rapidly:

$$\frac{1}{\bar{w}} = \frac{\int_{\ln a_{\rm tr}}^{0} \Omega_{\rm d}(a)/w(a) \, d \ln a}{\int_{\ln a_{\rm tr}}^{0} \Omega_{\rm d}(a) \, d \ln a}. \tag{26}$$

In many cases, the present equation of state, $w_{\rm d}^0$, can be used as an approximation to $\bar{w}$ since the integrals are dominated by periods with large $\Omega_{\rm d}$. (In general, $\bar{w} \neq \bar{w}_0$, Eq. (20).) The scale factor at matter radiation equality is

$$a_{\rm eq} = \frac{\Omega_{\rm r}^0}{\Omega_{\rm m}^0} = \frac{4.31 \times 10^{-5}}{h^2(1 - \Omega_{\rm d}^0)}. \tag{27}$$

Finally, the conformal age of the universe τ_0 is given by eq. (18). Equation (24) in combination with (23) can be used to make general statements about the consistency of quintessence models with σ_8-constraints.

The CMB-normalized value of σ_8 depends on all cosmological parameters. As a rough guide for the strength of these dependencies around standard values $\Omega_{\rm d}^0 = 0.65$, $h = 0.65$, spectral index $\hat{n} = 1$, $\Omega_b h^2 = 0.02$ with $-1 < \bar{w} < -0.5$ we get

- Increasing h by 0.1 $\Rightarrow$ Increase of σ_8 by 20 %
- Increasing $\Omega_{\rm d}^0$ by 0.1 $\Rightarrow$ Decrease of σ_8 by 20%
- Increasing $\hat{n}$ by 0.1 $\Rightarrow$ Increase of σ_8 by 25%
- Increasing $\bar{w}$ by 0.1 $\Rightarrow$ Decrease of σ_8 by 5-10%
- Increasing $\Omega_b h^2$ by 0.01 $\Rightarrow$ Decrease of σ_8 by 10%
- Increasing $\bar{\Omega}_{\rm d}^{\rm sf}$ by 0.1 $\Rightarrow$ Decrease of σ_8 by 50%

Comparing with observation, the dependencies listed can be used for a quick check of viability for a given quintessence model and parameter set. If $\Omega_{\rm d}^0$ is increased by 0.1, cluster abundances according to Eq. (23) yield an approx. 20% higher value of $\sigma_8^{\rm cluster}$. In combination with the corresponding decrease of $\sigma_8^{\rm cmb}$, the net effect on the ratio $\sigma_8^{\rm cmb}/\sigma_8^{\rm cluster}$ is therefore a decrease by 33%. For a ΛCDM universe with standard values as above one has $\sigma_8^{\rm cmb} = 0.90$ and $\sigma_8^{\rm cmb}/\sigma_8^{\rm cluster} = 1.01 \pm 0.2$. Compatibility of the cosmological scenario requires this ratio to be close to unity.

In particular, we note the degeneracy between the amount of dark energy during structure formation $\bar{\Omega}_d^{sf}$ and the spectral index $\hat{n}$, as shown in fig. 3. In this context it

may be useful to recall that the smallness of the density fluctuations could find a natural explanation within inflation without invoking small parameters or mass ratios if $\hat{n} \approx 1.15$ [34].

Constraints from structure formation may be combined with the CMB-data to constrain specific models of quintessence [27]. For a specific quintessence model one may further use the supernovae results [10]. They constrain the very recent increase of Ω_d, or, equivalently, the present equation of state w_d^0. For leaping kinetic term quintessence the value of w_d^0 is, however, not directly related to Ω_d^{ls} or Ω_d^{sf} since it is strongly influenced by the width and height of the leap (generalizing eq. (15)). We conclude that some particular models of quintessence are disfavored already by the present data, as, for example, power law potentials [27]. Other models, like leaping kinetic term quintessence [19], are consistent with present observations, allowing early quintessence on a level of $\Omega_d \lesssim 0.2$ during nucleosynthesis, structure formation and last scattering. With forthcoming observations it should be possible to improve the constraints substantially and to distinguish between quintessence and a cosmological constant.

Observation seems to tell us that for a viable model of quintessence the fraction of dark energy Ω_d has increased substantially in recent time, say from 0.1 to 0.7. Even though an increase by a factor of 7 since the Planck epoch is mild as compared to the factor $\sim 10^{120}$ for a cosmological constant, it has happened during a relatively short cosmological period and singles out the present epoch. So far, phenomenological models of quintessence can deal with this by adjusting a suitable parameter on the percent level. We feel, however, that this answer to the question “why now” is not very satisfactory. In our view, quintessence would become more credible if the recent increase in Ω_d can be induced by a recent characteristic event in cosmology, like the formation of structure. Cosmon dark matter [18] could give such an explanation. It would also lead to a revision of the present picture of cold dark matter and structure formation. We should not be surprised if quintessence leads us to further changes of our picture of the universe!

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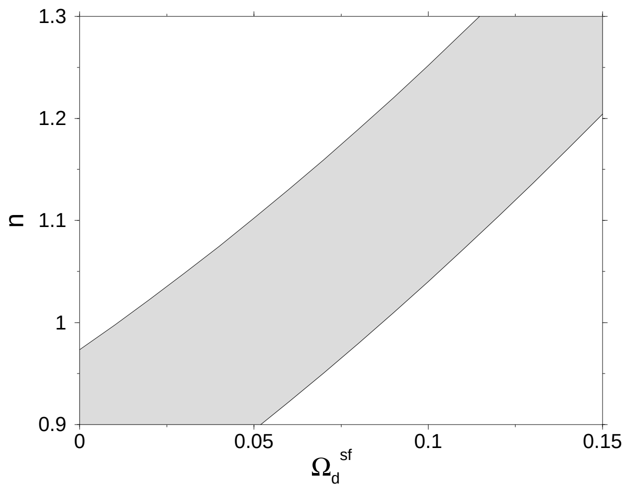

(a) $h = 0.7,\ \Omega_{\rm d}^0 = 0.6$

Figure 3: Allowed range of early quintessence and spectral index $\hat{n}$ for given values of the Hubble parameter h and present dark energy $\Omega_{\rm d}^0$.

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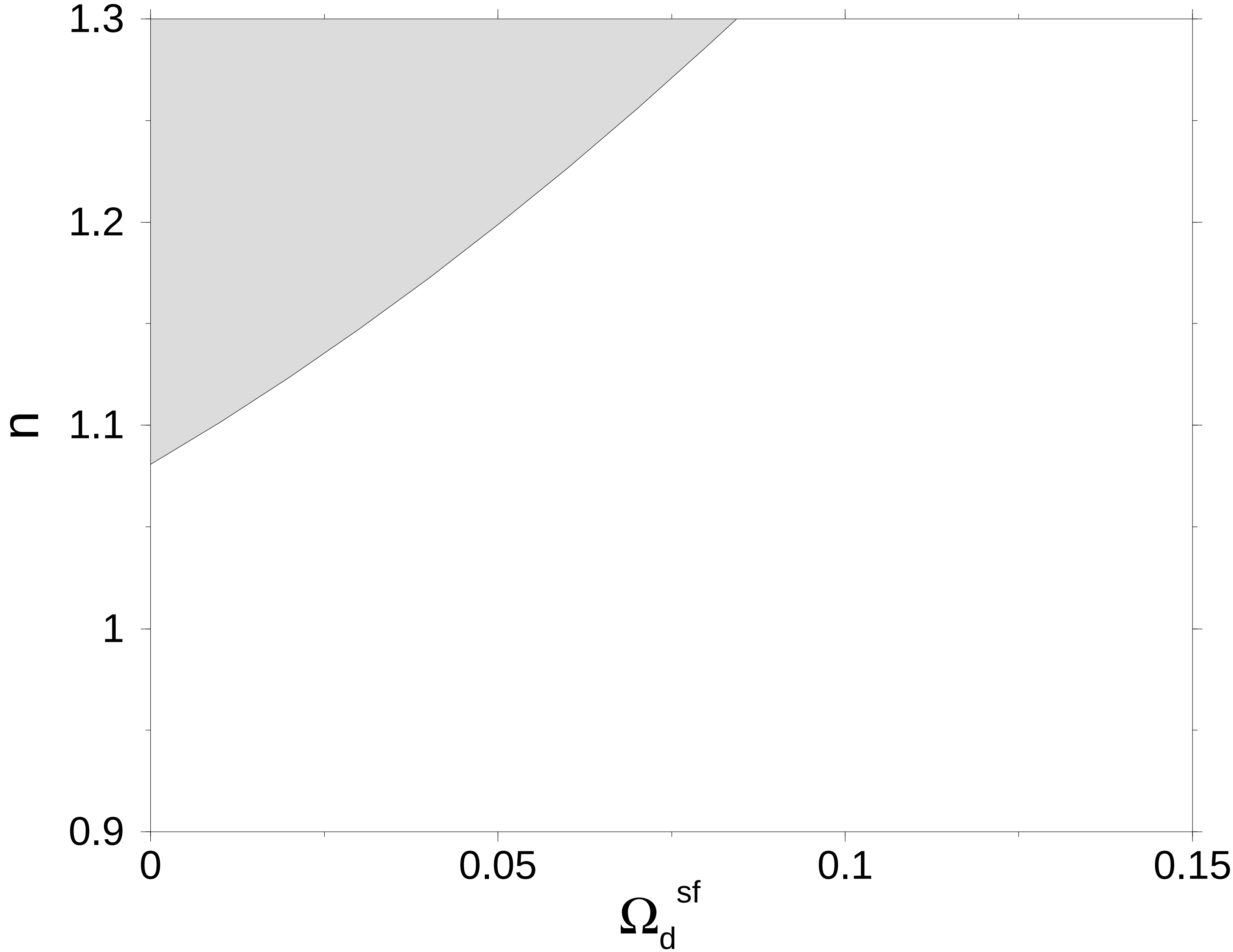

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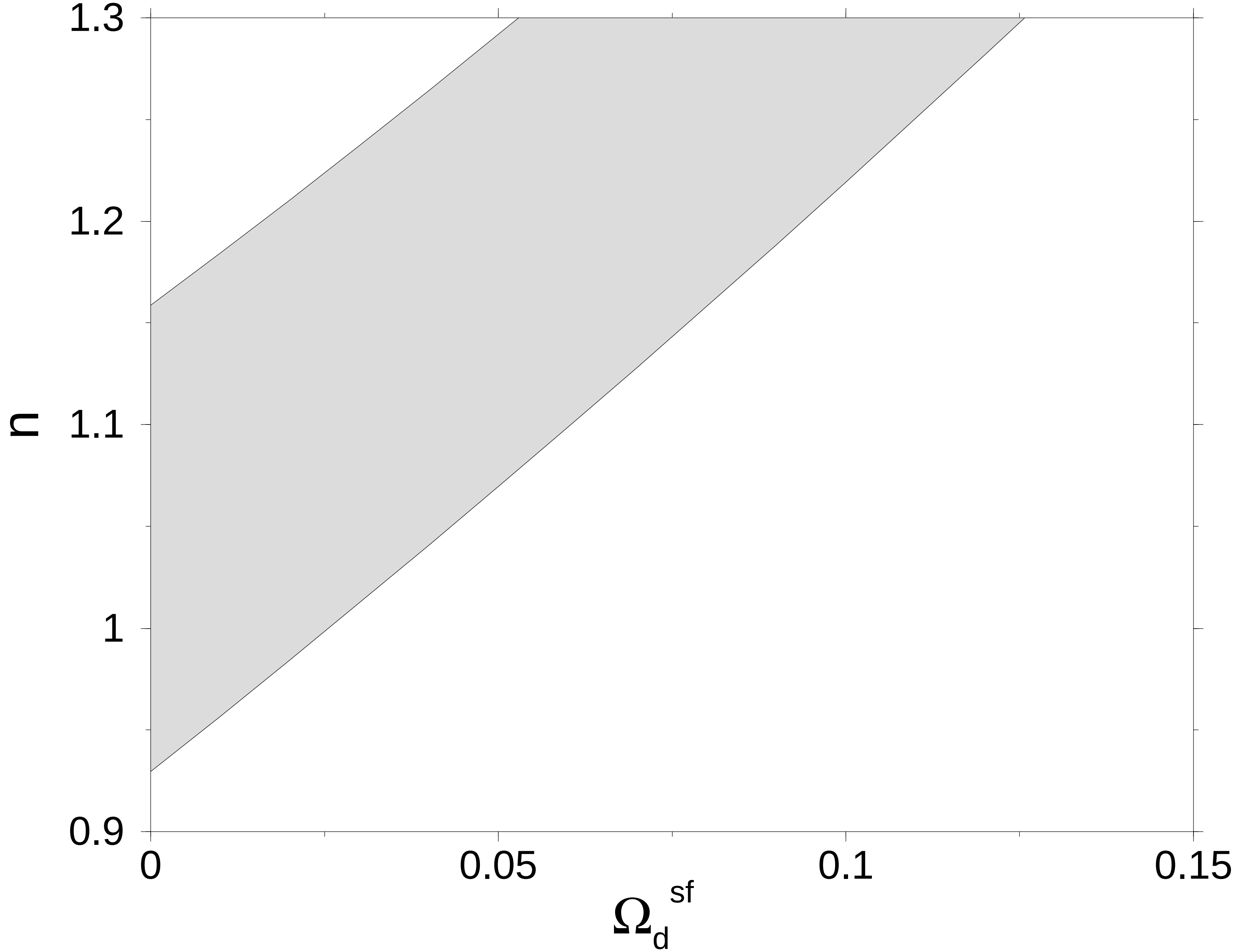
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